GROUNDWATER AND VOLCANIC VOLATILES

INTRODUCTION

(Terms in bold included in Glossary)

Volcanoes emit large quantities of CO_2 to the atmosphere every year, as well as compounds of sulfur, chlorine, and fluorine. An important part of the USGS mission involves quantifying the emissions and deciphering what they tell us about subsurface conditions **(Volcanic Emissions)**. Not all of the volatile species released at volcanoes escape directly to the atmosphere, however. Unerupted **magma** releases volatiles deep within or beneath the volcano. Many of the volatiles are very soluble in water, and, as they rise toward the earth's surface, dissolve into groundwaters or crater lakes. Much of this dissolved gas may subsequently reach the atmosphere when opportunities permit it to come back out of solution, for example at a spring discharge. Subsurface reactions convert some dissolved gas into non-volatile compounds; for example, CO_2 can be converted into HCO_3^- and H_2S can be converted into SO_4^{-2}. Some of these compounds get incorporated into **alteration minerals** and never reach the earth's surface. A complete study of magmatic emissions must account for the dissolved gas transported by groundwater, whatever its ultimate fate.

Hydrothermal systems with **hot springs** or **fumaroles** are very visible features in many parts of the world, and it has long been known that these features commonly contain gases that were released from magma at depth. Most gases are much more soluble in cold water than hot; for example, CO_2 is 8 times more soluble at 5°C than at 175°C. Magmatic CO_2 that escapes through deep hydrothermal fluids can thus be absorbed in large quantities by overlying cold **aquifers**. Over the past decade, more and more cold waters have been found that contain substantial quantities of **magmatic CO_2**, frequently accompanied by **magmatic helium**. This site presents the results of our investigations of mostly cold waters in volcanic areas that potentially transport magmatic gas. For a discussion of monitoring efforts focused on hydrothermal fluids, see this Hydrothermal Discharge document.

This document is divided into descriptions and maps of the various features, discussions of the study areas, and tables of chemical data. For additional technical information, please contact Bill Evans (wcevans@usgs.gov) at the U.S. Geological Survey. This website focuses on the geochemical aspects of volcano-groundwater interactions. For information on the hydrologic hazards associated with volcanoes, such as break-out floods and debris flows, visit the **Volcano Hydrology website**. For information on the role of water in explosive eruptions, visit the **Volcano Gas and Water website**.

GLOBAL CO_2 EMISSIONS

Samples collected from this cold spring near Mammoth Mountain showed that it discharged many tonnes per day of dissolved magmatic carbon.

Direct measurements of CO_2 **flux** from volcanoes have been made in enough places to provide a basis for estimating the global emission rate. **Subaerial** volcanoes are currently thought to release about 10^8 **tonnes** of CO_2 to the atmosphere every year. This value is heavily weighted by the emission rate of a few major emitters like Mt. Etna in Sicily and Kilauea in Hawaii. The global emission rate may consequently vary substantially through time, dropping drastically when no major emitters are active.

Attempts to quantify the magmatic carbon discharge in cold groundwaters are relatively new, and the total amount transported by groundwater globally is not known. Regardless, the magmatic carbon dissolved in cold groundwaters is an important part of the picture at many individual volcanoes, as demonstrated by our findings at **Mammoth Mountain (USA)**, **Lassen Peak (USA)**, and **Lakes Nyos and Monoun (Cameroon)**. Some recent studies have now suggested that such transport may be an important part of magmatic degassing on a global basis. Groundwater transport of magmatic carbon is probably very widespread and at individual volcanoes, probably of longer duration than episodic periods of summit plume emissions. It may thus serve to smooth out variations in the global emission rate over **geologic time**.

Dissolved CO_2 from any source can be converted into HCO_3^- or CO_3^{-2}, and studies of magmatic carbon in groundwater must therefore look at the sum of all these species, called the **DIC** (dissolved inorganic carbon). Some carbon from biogenic sources, such as soil respiration, accompanies the DIC derived from magmatic sources in all groundwaters, and a major effort is sometimes needed to separate the contribution of these different sources. A detailed look at water chemistry and **isotopes** can be an invaluable tool in these efforts, leading to the data tables presented on this site.

References:

Barnes et al., 1981
Gerlach, 1991
Brantley and Koepenick, 1995
Rose and Davisson, 1996
Chiodini et al., 2000
Evans et al., 2002

MAMMOTH MOUNTAIN - LONG VALLEY CALDERA

100 tonnes/day of magmatic CO_2 effuse through the soils near Horseshoe Lake.

The Long Valley **caldera** in eastern California was formed by an enormous eruption about 750,000 years ago. Volcanism in this area has continued to the present, with the most recent eruptive activity in the Inyo craters chain about 700 years ago. An ongoing period of unrest and uplift under the **resurgent dome** in the center of the caldera began in 1980. The Long Valley caldera is under thorough and continuous surveillance by the USGS, and a Scientist-In Charge has been appointed to coordinate all of the work that is done in this popular recreation area
(**Long Valley Caldera website**). The caldera hosts a large hydrothermal system with boiling springs and fumaroles and a 40 Megawatt power generation plant at Casa Diablo. A large number of studies have been done on the hydrothermal system (**Hydrothermal monitoring at Long Valley**), and only a few of them are described on this site.

Mammoth Mountain is a mostly **dacitic** volcano on the southwestern rim of the Long Valley caldera. It was built up in stages over the past 200,000 years. Unrest at Mammoth Mountain became a concern in 1989, when seismic evidence suggested the **intrusion** of a thin dike a few km below the mountain. This was followed within months by changes in steam flow and geochemistry in a small fumarole on the northeast side of the mountain. More unusual was an outpouring of cold CO_2 through broad areas of soil on the flanks of the mountain that ultimately led to the death of 50 ha of mature coniferous forest. A number of studies have focused on this unusual phenomenon (**Mammoth Mountain CO_2 gas monitoring website**).

The interest in the CO_2 discharge at Mammoth Mountain led to an investigation of the springs and wells around the base of the mountain, many of which were found to be rich in magmatic DIC even though they were cold and otherwise dilute. Sampling began in 1996, and by 1998, most sites had been sampled at least once. Sampling has been repeated at in different seasons and years at many of the sites to assess the short-and long-term variability in chemistry and flow rate. This is the main reason that some of the features appear many times in the data tables.



In the first photo, there is a large patch of trees killed by CO_2 (left side of photo) which can be seen from miles away. In photo two, Spring discharges are gaged to accurately determine water flows. The concentration of dissolved magmatic carbon in each spring is combined with it's gaged flow to determine total magmatic carbon output.

References:
Bailey, 1989
Sorey et al., 1991
Farrar et al., 1995
Sorey et al., 1998 Evans et al., 2002

MAMMOTH MOUNTAIN SITE DESCRIPTIONS

Although the combined flow from the thermal and mineral springs RMT, USC, and DPP is only a few L/s, a long sampling history exists for these features (e.g., Barnes et al., 1981; Farrar et al., 1987; Shevenell et al., 1987; White et al., 1990; Sorey et al., 1993). None of these springs has shown notable changes in temperature, chemistry, or isotopic values following the magmatic intrusion in 1989.

(RMT) The source of heat and volatiles for this 47°C spring has been discussed by Shevenell et al. (1987) and Sorey et al. (1993), but some uncertainties remain. The water is low in [O_2] and moderately mineralized but also contains significant tritium (Shevenell et al., 1987). It may be a relatively young groundwater that has been steam-heated, or may have circulated through a shallow region where the rock retains some heat from previous intrusions. The d^{13}C-DIC value of -6.0 and $^3He/^4He$ of 2.6 R_A suggest a connection to the Mammoth Mountain gas source. Regardless, its DIC discharge constitutes a tiny fraction of the total from Mammoth Mountain.

(USC and DPP) These soda springs discharge bubbles of CO_2 and small amounts of mineralized fluid containing red iron-oxyhydroxide precipitates. The springs rise at the edge of the San Joaquin River and are seasonally underwater. The recharge area for these springs is unclear as they discharge off the Mammoth Mountain edifice. The gas in these springs could be sourced beneath Mammoth Mountain, but the $^3He/^4He$ at DPP is low, 0.48 R_A, and similar types of springs are scattered throughout the Sierra Nevadan batholith with no clear tie to volcanics. The DIC discharge from these springs is trivial.

Cold, dilute springs and wells

Reds Creek area

(RMCS) This spring group forms the headwaters of the perennial part of Reds Creek. None of the many orifices contains free gas bubbles, but water collected in a beaker quickly forms bubbles on the walls. Interestingly, the outflow stream passes within 2 m of the hot spring RMT, and has been used for decades to cool the hot water prior to its use in a bathhouse. Despite the fact that the DIC discharge from RMCS dwarfs that from the hot spring, our sampling of this spring group in 1996 was the first revelation of the huge DIC component in the Mammoth Mountain cold springs.

(SLS) This spring group produces weakly thermal water with sporadic pulses of gas bubbles. The outflow drains into Reds Creek below RMT. This feature may contain a component of RMT-type fluid to account for its low K/Na and Mg/Na ratios and the high [F] and [B] relative to the other Mammoth Mountain springs.

(SJTAT) This spring is representative of several low-flow, widely spaced springs between Reds Creek and Boundary Creek, all of which produce CO_2-rich water near the 2500-m elevation contour. We estimate that the total flow from all such features is 10-20 L/s. This vent was chosen for sampling because it contains some free gas bubbles.

Boundary Creek area

(LBCN, LBC, LBCS) These features are actually three groups of springs, each comprising many orifices, that issue in close proximity. The LBC group forms the headwaters of the perennial part of Boundary Creek, and the LBCN group flows into Boundary Creek about 100 m downstream. The LBCS group issues ~50 m away from Boundary Creek, but the water flows south and eventually joins Crater Creek. Gas bubbles have been sampled in vents at both LBCN and LBCS areas.

(ASS) All of the flow from this feature occurs from a single large, vent, 10 m in diameter. This is the southernmost high-flow cold spring draining Mammoth Mountain and discharges into Crater Creek.

(CCS) This feature is a low-flow seep with a slightly elevated [DIC]. It appears to contain some anomalous carbon from Mammoth Mountain, but likely consists mainly of groundwater from the granitic ridge to the southeast. It is chemically distinct from the nearby LBC and ASS springs in having low K/Na, Mg/Na, and [PO_4^{-3}], and elevated [F^-].

Dry Creek area

The Dry Creek drainage runs down the northeast side of Mammoth Mountain and ends ~20 km away at the northern margin of the Long Valley caldera. Dry Creek is normally dry beyond the West Moat. Discharge from the Dry Creek groundwater system is commonly assumed to occur at Big Springs (BS). Groundwater flow from Mammoth Mountain all the way to BS has never been demonstrated, but a recent study of hydraulic head gradient, transmissivities, volcanic stratigraphy, and some chemical and isotopic data has supported this connection (Heim, 1991). The large andesite flow near BS is representative of many buried flows of andesite and basalt, some thought to originate near Mammoth Mountain, that form possible aquifers.

Much of the north side of Mammoth Mountain is covered by ski runs. Ski-area operators apply salt (NaCl) to the runs to improve skiing conditions. Regulations limit the amount of salt that can be applied each winter, but after the limit is reached, NH_4NO_3 can be applied for the same purpose. Because naturally occurring Cl^- and NO_3^- are low in the cold groundwaters, infiltrating snowmelt from the ski area can be traced through the groundwater system.

(MINS) This low-discharge spring issues near the Minaret summit drainage divide. It is only slightly enriched in DIC but contains an abiogenic carbon component. This is one of the few cold springs on the mountain for which $d^{13}C$-DIC data exist prior to 1989 (Farrar et al., 1985).

(CH12S) This spring is the highest in elevation, has the lowest pH, and the most abundant gas bubbles of all the cold springs. It rises in close proximity to the CH12 tree-kill area and its discharge channel flows past the main ski lodge. A well (CH12W) was drilled nearby in 1999 and encountered similar water at ~30 m depth. The slight anomalies in NO_3^- and Cl^- may result from ski-run salting.

(MLS, MMSA1, MMSA2B, MMSA3) MLS is a small ephemeral spring that flows only for a short period following snow melt and issues a few meters away from the main ski lodge where several runs terminate. MMSA1 (37 m deep) and MMSA2B (100 m deep) are pumped wells, and MMSA3 is either a shallow artesian well or spring that fills a concrete tank. These wells supply water that is used for snow-making at the ski area. According to ski-area personnel, MMSA1 and 2 have produced CO_2-rich water from the time that they were drilled in 1958 and 1982, respectively. These features all show the clear influence of ski-run salting, having high [NO_3^-], [CL^-]/[Br^-], and [CL^-]/[B].

(DCWELL2, DCWELL6) These unused wells were drilled in the late 1980's for eventual water supply to the town of Mammoth Lakes. Their location 1-2 km down the Dry Creek drainage from the ski-area wells is important to the study of groundwater flow away from Mammoth Mountain. Previous chemical analyses exist for these wells (Heim, 1991).

(CTRAW, CTW2, BS) CTRAW is a 100 m-deep well that supplies water to a roadside rest area. It is located 8 km down the Dry Creek drainage from DCWELL2 and 6, and 2 km up-gradient from BS. CTW2 is a 100 m-deep well tapping groundwater from the northwest rim of the caldera in the Glass Creek drainage. The warm temperature we measured probably reflects solar heating of the discharge pipe. Big Springs (BS) forms the headwaters of the Owens River. Groundwaters from the Dry Creek, the Glass Creek, and the Deadman Creek drainages are all thought to discharge here through many orifices spread over hundreds of meters of channel.

Lakes Basin area

(VSS) This spring was reportedly the main water supply for the lodge at the Valentine Reserve until it suddenly became gassy in the early 1950's, following a local earthquake. An old pipe system from the spring box to the lodge testifies to its former use. Unused today, it drains into Mammoth Creek.

(PDS, TLS, LB-1, CH15S, PSBBC) An assortment of small springs and wells that contain some abiogenic carbon, these features contribute a small fraction of the total DIC discharge. PDS may drain areas south of Mammoth Mountain containing marine carbonates. TLS, with a slightly heavy $d^{18}O$, may contain subsurface leakage from one of the lakes upgradient. LB-1 is a water-supply well for local cabins. CH15S is located at the base of a concrete abuttment where a ski run passes over a highway tunnel. This feature is one of the few dilute springs that has become anoxic, depositing red iron oxyhydroxides around the orifice. PSBBC flows from a driven pipe in an area of groundwater seepage near the shore and beneath the surface of Twin Lakes. The total seepage here is sizeable and sufficient to greatly alter the chemical and isotopic characteristics of the lake water, as can be seen by comparing the inlet (TWIN-In) and outlet (TWIN-Out) values. TWIN-In has a water chemistry reflecting the granitic rock in the catchment, for example, a low [Mg]/[Na] and [Cl^-]. TWIN-Out is enriched in [Mg]/[Na] and heavily depleted in ^{14}C. In these surface waters, [SiO_2] is maintained at low levels by diatom growth. The seepage of high-DIC fluid like PSBBC causes the pCO_2 at the outlet to be greater than in air. Loss of CO_2 from the surface of Twin Lakes probably causes the magmatic DIC contribution from seepage to be somewhat underestimated.

References

Barnes, I., Kistler, R. W., Mariner, R. H., Presser, T. S., 1981. Geochemical evidence on the nature of the basement rocks of the Sierra Nevada, California. U. S. Geol. Surv. Water-Supply Pap. 2181, 13 pp.

Barnes, I., Irwin, W. P., White, D. E., 1984. Global distribution of carbon dioxide discharges and major zones of seismicity. U. S. Geol. Surv. Misc. Invest. Map I-1528, 10 pp.

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Heim, K., 1991. Hydrologic study of the Big Springs, Mono County, California, senior thesis prepared for Mammoth County Water District, Mammoth Lakes, California. Calif. State Univ. Fullerton. 79 pp.

Shevenell, L., Goff, F., Grigsby, C. O., Janik, C. J., Trujillo, P. E., Jr., Counce, D., 1987. Chemical and isotopic characteristics of thermal fluids in the Long Valley caldera lateral flow system, California. Trans. Geotherm. Resour. Council 11, 195-201.

Sorey, M. L., Kennedy, B. M., Evans, W. C., Farrar, C. D., Suemnicht, G. A., 1993. Helium isotope and gas discharge variations associated with crustal unrest in Long Valley caldera, California. J. Geophys. Res. B98, 15,871-15,889.

White, A. F., Petersen, M. L., Wollenberg, H., Flexser, S., 1990. Sources and fractionation processes influencing the isotopic distribution of H, O, and C, in the Long Valley hydrothermal system, California, U.S.A. Appl. Geochem. 5, 571-585.

BIG SPRINGS

Most of the flow in the Owens River, shown here, derives from a series of springs that make up the Big Springs complex.

Big Springs is a high-flow group of springs that forms the headwaters of the Owens River. These springs have the largest flow of any of the springs in the area. The springs issue at the northern margin of the Long Valley **caldera** about 15 km NE of Mammoth Mountain, and they are thought to drain groundwater systems from both inside and outside the caldera. Our study of the springs was started mainly as an effort to determine if any of the **dead carbon** in the spring water could derive from Mammoth Mountain. Groundwater flow from Mammoth Mountain to Big Springs has been hypothesized, but never proven.

The Big Springs study also represents a chance to test new methods of groundwater tracing. Groundwater is an important resource in this area, and a knowledge of flow direction and time is needed to evaluate the impact of development. In particular, the impact of well pumping on Big Springs is a question of importance to many people living in the area.

REFERENCES:
Farrar et al., 1985
Farrar et al., 1987
Reid et al., 1998
Evans et al., 2001
Evans et al., 2002

HOT CREEK

Travertine deposits from the springs in Hot Creek surround visiting tourists.

Hot Creek is formed by a set of large hot springs, many at boiling temperature, that discharge into Mammoth Creek. This set of springs is the main discharge point for liquid from the large **hydrothermal system** in the Long Valley **caldera**, although a few hot springs discharge from this same system elsewhere in the caldera, and much steam discharges up-gradient at the Casa Diablo power plant. Hot Creek is a popular tourist stop, affording bathing in warm pools where the hot water mixes with the cold Mammoth Creek. Injuries from scalding and even a few fatalities have occurred here, so the area is monitored by Forest Service personnel and is closed to access at night.

Mammoth Creek is fed mainly by snowmelt off the Sierran crest and is dilute. The hot spring water is high in many dissolved species including fluoride, chloride, and arsenic. The total input of water and chemical species has been monitored at different times and for different purposes over the years. Our monitoring was prompted by a desire to see if hot spring discharge correlates with unrest **(Hot Creek Gorge)**. Most of the monitoring studies take the same approach. Mammoth Creek is sampled above and below the hot spring input, and the flow of the creek is determined by **gaging**. From the increase in the concentration of any substance over this stretch of stream, the total input of that substance can be determined. If the concentration of that same substance in the hot spring water is known, then the total input of hot water can be calculated. This later calculation assumes that all the hot spring water has the same composition.

References:
Sorey et al., 1991

ISOBUTANE

Geothermal power plant, in foreground, uses isobutane to drive the turbine.

The large **hydrothermal system** in the Long Valley **caldera** is thought to flow laterally southeast from an **up-flow zone** in the West **Moat**. **Fumaroles** form at places where **permeable zones** allow steam and gas from the hot fluid to reach the surface. A 40 MWe power plant has been built at one of these places, Casa Diablo. The plant pumps hot water up into a **heat exchanger** where **isobutane** is heated by the water. The isobutane vaporizes at high pressures to drive a turbine. The cooled water is then pumped back down into the ground. Occasionally, a leak develops in the heat exchanger, allowing isobutane to enter the water stream and be pumped down into the ground. Once in the aquifer, the isobutane flows with the hot water until it can boil out in a fumarolic area. It has been detected in fumaroles many km from Casa Diablo and offers proof that the underground water has been through the heat exchanger.

Isobutane is a useful tracer for a number of reasons. It is inert for long periods at the temperatures and pressures of geothermal systems and is probably not appreciably adsorbed onto solid surfaces. It normally occurs naturally in only trace amounts except in areas where petroleum/natural gas occurs. It is easily detected by **gas**

chromatography. It has a very low aqueous solubility so that it will readily separate into the vapor phase, and its presence in fumaroles will reveal the flow at depth of isobutane-tagged water. Thus it can be used in places where the liquid phase does not reach the surface. It can be used to compliment tracers that stay in the liquid phase to study boiling between **injection and production wells**.

REFERENCES:
Sorey et al., 1991

LASSEN PEAK, CALIFORNIA

Lassen Peak viewed from Lake Helen.

Lassen volcano **(CalVO: Lassen)**, in northeastern California, was last active 1914-1917, with summit eruptions and **debris flows** devastating a large area on the flanks. Lassen supports a large **hydrothermal system** with outflow of hot water to the south and east. Recent studies have shown that magmatic carbon is present in some of the high-discharge cold springs north of Lassen, prompting a more detailed study of the many cold springs around the volcano's flanks. This work is not yet complete but has identified a few cold springs very rich in magmatic DIC.

View a map of Lassen peak here.

References:
Rose et al., 1996
Evans et al., 2002

THREE SISTERS, OREGON

Middle Sister viewed from Separation Creek Meadows.

Separation Creek on the western side of South Sister volcano in central Oregon has been known to discharge anomalous chloride since the late 1980's. The source of the chloride anomaly was eventually traced to a **hydrothermal water** component in springs scattered widely throughout the drainage. The thermal component in individual springs is small. The maximum chloride concentration in any spring is about 20 mg/L, and the maximum temperature anomaly is about 5°C above ambient. However, the total discharge of anomalous chloride over the entire drainage is about 10 g/s, and the total discharge of anomalous heat is about 16MW. Thus, almost as much hydrothermal fluid discharges in the Separation Creek drainage as in the large, low-elevation **hot springs** in this region.

In 1998, a >100 km^2 area centered in the Separation Creek drainage began to bulge up at the rate of about 4-5 cm/yr, leading to speculation of a magmatic **intrusion**. The discovery of this uplift in 2001 **(Sisters Uplift)** by satellite interferometry imaging (InSAR) led to an increased interest in sampling and monitoring the springs in the area. Data from the 2001 and subsequent investigations appears in the **analytical data** tables and can be viewed in report form at **Separation Creek, 2001**. Some of the data from previous investigations, carried out mostly by Steve Ingebritsen and Justin Iverson, are shown in **Separation Creek** and are plotted along with newer results on the **Big Sisters map**. An investigation of the **DIC** has revealed a clear isotopic signal of magmatic carbon. Although the concentration of magmatic DIC in the springs sampled so far is limited to a few mmol/L, the DIC anomaly, like that of chloride and heat, is widespread through the drainage and could total as much as 20 tonnes/day of magmatic CO_2. Because the chloride anomaly predates the current period of crustal uplift, it is not at all clear if any of this magmatic CO_2 can be tied directly to a new intrusion. However, the ongoing uplift demands serious efforts to monitor the discharge of magmatic carbon in this area.

References:
Mariner et al., 1990
Ingebritsen et al., 1994
Iverson, 1999
James et al., 1999
Manga, 2001
Wicks et al., 2001
Van Soest et al., 2001

LAKES NYOS AND MONOUN, CAMEROON

These two lakes released large clouds of CO_2 gas in the 1980's, killing nearly two thousand people. The events offer dramatic evidence of the power of cold groundwater to hold magmatic CO_2 in solution. Groundwater circulating in the **diatreme** underlying these crater lakes absorbed magmatic CO_2 and carried it up into the lake's bottom layers. An **overturn** of the water column allowed the gas to come out of solution rapidly and catastrophically.

More information can be found at the **Cameroon Lakes** website, maintained by the University of Michigan.

References:
Sigurdsson et al., 1987
Kling et al., 1987
Evans et al., 1994
Kusakabe et al., 2000

SELECTED GEOCHEMICAL DATA FROM SPRINGS AND WELLS

A tabulation of **analytical data** obtained since 1995 during investigations of magmatic gas in groundwater, gas-water-rock interactions, gas and solute fluxes, and groundwater discharge on and around various volcanoes. The table will be periodically updated. Every effort has been made to keep this table error-free, but for critical applications, the original analytical printouts should be checked. Please contact Bill Evans at the USGS for further information.

All pages containing data from any given study area appear consecutively. The first page for each study area gives location information and a brief description of the site. Subsequent pages show different types of analytical results. Samples collected within a study area are numbered sequentially on the pages, and for features sampled more than once, a new number is assigned for each collection date. Many of the sampling sites are shown on the maps elsewhere on this site.

The analytical results, and in many cases, sample collection, involves the work of many collaborators from within USGS and other agencies or universities. All anion analyses were performed by Mark Huebner. Stable isotopes of water and carbon were measured by Doug White. Noble gas isotopes were measured at LBNL by Mack Kennedy, Dave Shuster, or Thijs van Soest. Carbon-14 measurements were performed at LLNL by Andrea Cook, John Southon, or Tom Guilderson. Mike Sorey, Liz Colvard, Chris Farrar, Cathy Janik, Bob Mariner, and John Rogie, were involved in field measurements and sample collection.

GLOSSARY

The definitions given here are not meant to be complete definitions for these terms but are provided to help explain the terms as used on this site. A thorough glossary of terms useful in volcanology can be found at the USGS website: **Volcanology Glossary**

Alteration minerals: Minerals that form as cold or hydrothermal waters react with the rock through which they flow.

Aquifer: Permeable zones in the earth through which groundwater can flow to springs and wells.

Caldera: A large volcanic crater or depression that may contain or be surrounded by several individual volcanoes, craters, or domes.

Dacitic: A viscous type of lava characterized by certain chemical criteria.

Dead carbon: Carbon compounds in living plants and animals contain the isotope ^{14}C. Carbon from magma or other geologic sources does not, and is called dead carbon.

Debris flows: A flow of rock fragments and mud. These flows can reach high speeds and destroy forests or structures in their path.

Diatreme: A pipe-like conduit filled with debris and solidified magma that underlies a crater formed in a gaseous eruption.

DIC: Dissolved Inorganic Carbon.

Dissolved Inorganic Carbon: The carbon dioxide (CO_2) plus the related bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) that are dissolved in a water.

Flux: The mass discharge rate to the atmosphere over a given area.

Fumarole: A vent that releases steam and gases.

Gaging: Measuring the flow of water in a stream usually done by determining the depth and velocity at many different points across the stream.

Gas chromatograph: Machine that separates and identifies the components in a sample of a gas mixture.

Geologic time: The long time periods, for example millions of years, over which geologic processes operate.

Heat exchanger: A large tank that receives the hydrothermal water from the pumped wells. Pipes inside the tank carry isobutane, which is heated and vaporized by the water.

Hot spring: A spring that discharges hot water. Some hot springs discharge at boiling temperatures.

Hydrothermal systems: Aquifers or underground reservoirs containing water that has become heated to high temperatures by deep circulation or buried magma.

Hydrothermal water: The hot water in the hydrothermal systems.

Injection and production wells: Hydrothermal water is pumped up the production wells and pumped back down the injection wells after its heat is extracted.

Intrusion: The movement of magma into preexisting rock.

Isobutane: Organic compound with a boiling temperature that makes it a suitable working fluid in a geothermal power plant.

Isotopes: Each chemical element, for example carbon or helium, exists in more than one isotope, which differ in the number of neutrons. Isotopic ratios can sometimes be used to determine the origin of chemical species.

Magma: Molten rock generated within the earth. Magma can rise to the earth's surface and issue forth as lava, or it can cool and solidify within the earth.

Magmatic CO_2: Carbon dioxide that is originally dissolved in magma at depth but that can escape from the magma as a free gas or into an aqueous solution.

Magmatic He: Helium that is originally dissolved in magma at depth. Magmatic helium is generally much richer in the light isotope (^3He) than atmospheric or crustal helium.

Moat: A low-lying area within the caldera between the rim and the resurgent dome.

Overturn: A mixing of the layers in a stratified lake.

Permeable zones: Layers in the rock that allow the through-flow of water.

Resurgent dome: A dome that rises up inside a previously formed crater or caldera.

Subaerial: Subaerial emissions are those released directly to the atmosphere by volcanoes on land. Not included are gases released by undersea volcanoes.

Tonnes: Metric form of ton equal to 1,000,000 grams.

Up-flow zone: A zone of vertical fractures or faults that allow hot water to rise up from depth, but not necessarily to the surface.

This document is a compilation of content previously on the U.S. Geological Survey's Water Resources website. It can be downloaded here.